The Smallest Drops of the Hottest Matter: Exploring the Small Size Limit of the Quark Gluon Plasma

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1 Introduction to the Physics of Heavy Ion Collisions

The hottest matter that currently exists in the universe is briefly created in the collisions of large nuclei which are smashed into each other while traveling nearly the speed of light in particle accelerators. Such collisions are called *heavy ion collisions* and, aside from their extreme temperature, provide a unique opportunity to study the strong force.

There are four fundamental forces in nature: gravity, electromagnetic, strong and weak. All interactions that we know of can be described through one of these interactions. In everyday life, we are most familiar with the first two of these forces. Gravity constrains massive objects near the earth and the electromagnetic force governs the electricity and chemistry that we use everyday. The strong and weak forces are nuclear forces and as such are somewhat more remote in daily experience, however are central to the existence of the universe as we know it.

Atoms consist of a central core, the nucleus, surrounded by electrons orbiting it in nearly empty space. The nucleus itself is composed of protons and neutrons (collectively termed *nucleons* bound tightly together and contains the vast majority of the mass of atoms (and thus visible matter) in a radius approximately 10^5 times smaller than the atomic radius. Protons have positive charge and neutrons are charge neutral, so the electromagnetic force cannot keep the nucleus together. A separate short range force, the *strong force* holds the nucleus together. The details of this force determine the properties of nuclei.

Protons and neutrons, collectively *nucleons*, themselves are not fundamental particles, but composed of quarks and gluons which are likewise held together by the strong force. Nominally, nucleons are composed of three quarks, held together by gluons. These quarks determine the quantum numbers of the nucleon. However, interactions inside the nucleon give rise to a sea of gluons and quark-antiquark pairs. This structure is hidden by *confinement*, the property of the strong force that stable matter carries no net color charge (color charge is the strong force equivalent of the more familiar electromagnetic charge).

1.1 The Strong Force at High Temperature

Confinement makes the study of the strong force necessarily more difficult than the electromagnetic force. In heavy ion collisions, the aim is to study the strong force by creating temperatures so high than the confining nature of the strong force is overcome and color charges are no longer confined within colorless bound states.

The way to get enough energy to create temperatures high enough to create this matter is to collide two nuclei together at nearly the speed of light. The kinetic energy of the incoming

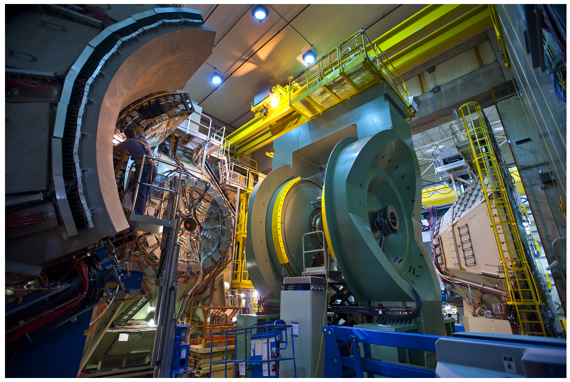

Figure 1: Picture of the PHENIX detector opened up and being worked on. Collisions happen in the center of the central magnet (large green object in the center) and particles fly outward from the center toward the detectors (some of which are visible). For scale, note the person working on the detector on the left. Photo available at Ref. [2].

nuclei is turned into heat by the collisions of the nucleons within the nuclei. As the particles interact they create a thermal system: the quark gluon plasma. The temperature created in these collisions has been measured by measuring the spectra of photons that radiate from the produced matter. The temperature right after the matter is formed is observed to be several trillion degrees Fahrenheit [1]. Unsurprisingly, very sophisticated equipment is required to collide pairs nuclei at speeds close to the speed of light. There are two machines in the world that are capable of this: the Relativistic Heavy Ion Collider (RHIC) at Brookhaven and the Large Hadron Collider (LHC) at CERN in Geneva.

Each drop of quark-gluon plasma is created in the collision between only two nuclei so the size of the nucleus (radius of about 7 $x10^{-15}$ m) sets the scale for the size of the quark gluon plasma. After the collision the matter expands and cools, existing for about $10 \cdot 10^{-23}$ s. As it cools off, it drops below the temperature at which the quark-gluon plasma can be formed and becomes normal matter.

Some of the initial kinetic energy of the nuclei is converted to mass ($E = mc^2$) and hundreds or thousands of new particles are created in each collision. These particles travel away from the collision point and are measured by the detectors. A picture of PHENIX, one of the two detectors currently operating at RHIC is shown in Figure 1. Since the collision region is so small and the produced matter exists for such a short time it is not possible to do anything to it in order to study it. Instead, experimenters measure as much as possible about the particles which leave the collision region and are measured with the detectors. That is the only information available about what happened in the collision. Starting with the particles that are measured, we work backward to infer the properties of the early stages of the collision.

2 Geometry in Collisions Between Two Large Nuclei

As many as thousands of particles are created in each collision, transforming some of the incoming kinetic energy of the nuclei into particles. Here we are going to discuss what the patterns in the particle production tell us about the initial geometry of the collision and the matter that was created.

Large nuclei have diameters of order 10×10^{-15} m. Given the extremely small size it might seem odd to discuss the geometry of heavy ion collisions. However, nuclei are composed of a finite

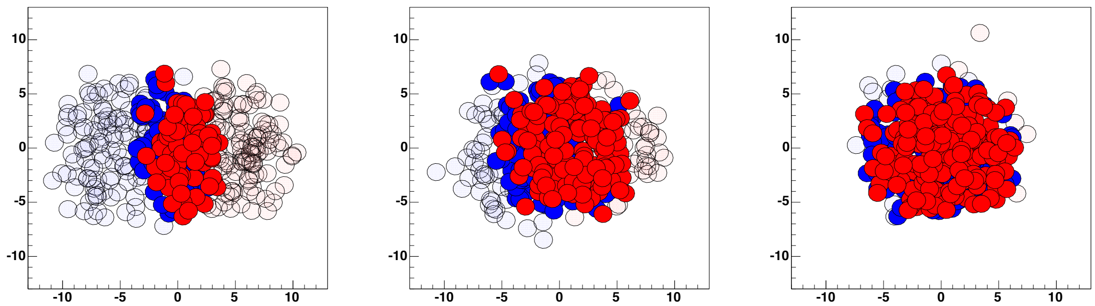

Figure 2: Illustrations of the nucleon positions for three simulated gold-gold collisions in the plane perpendicular to the incoming beam directions. Each circle represents one nucleon: red from one initial nucleus and blue from the other. Filled circles show the nucleons which collided with nucleons from the other nucleus and shaded circles show the nucleons which did not interact in the collision. From left to right the panels have a decreasing collision impact parameter.

number of nucleons, protons and neutrons. If the distance between the centers of the nuclei, the impact parameter b, is smaller than the nuclear radius the nuclei will directly collide. Fig. 2 shows the positions of nucleons from three simulated collisions of two gold nuclei, projected into the plane perpendicular to the incoming beam directions. The three panels show decreasing impact parameter (the impact parameter is the distance between the centers of the two nuclei as they collide) moving from left to right. Each gold nucleus is composed of 79 protons and 118 neutrons. These nucleons are depicted by the circles in the illustrations. The filled circles show the nucleons which participated in the collision and it is apparent that the *shape* of the region over which the two nuclei overlap is related to the impact parameter; as the impact parameter decreases the shape becomes more circular.

Somewhat amazingly, this shape can be seen in the angular distributions of particles around the beam direction (this angle is denoted as ϕ). Figure 3 (right) [3] shows the measured distributions of hadrons with respect to the angle ϕ, as defined in Figure 3 (left). As many as 20% more particles are observed in the long side of the overlap region (around $\phi = 0$ and $\phi = \pi$) than in the short side (around $\phi = \pm\pi/2$). The quantity v_2 is defined as:

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos(2\phi). \tag{1}$$

The observation of anisotropies immediately leads to the conclusion that the matter that is produced has significant interactions between its constituents. If the matter was a dilute (where the particle mean free path is large compared to the size of the system) gas then there would be no way for the particle to be altered depending in its direction relative to the geometry of the system. In that case, no matter the trajectory of the particle, the chance of interacting with another particle is small. At a higher particle density, the number of interactions will begin to depend on the particle's path length through the matter. What the large anisotropies observed in data tell us though is that the high interaction limit of liquid behavior is the more appropriate description. Rather than thinking about the matter as particles experiencing discrete interactions, the quark gluon plasma is more appropriately described as a fluid.

One way of characterizing any fluid is through its viscosity. For the quark-gluon plasma we characterize it in terms of the shear viscosity divided by the entropy density, η/s. In general, an increase in η/s leads to a reduction in the size the angular anisotropies observed in the data.

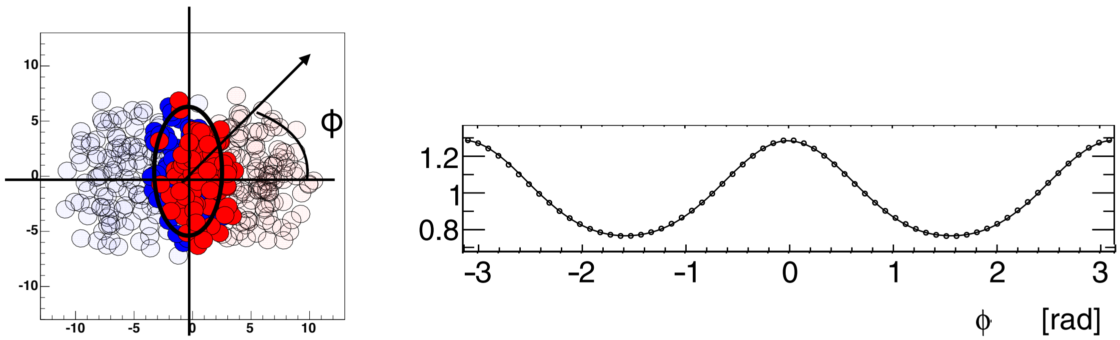

Figure 3: (left) Nucleus-nucleus collision illustration, now with the angle ϕ shown as the angle with respect to the impact parameter vector. (right) Angular distribution of charged particles from many lead-lead collisions at the LHC [3]. The angles are defined such that ϕ = 0 rad is aligned with the impact parameter vector as shown in the left panel. Note the suppressed zero on the y-axis.

Since, large anisotropies are observed, we conclude that the η/s of the quark gluon plasma has to be small. In fact, hydrodynamics calculations with zero viscosity comes close to describing the data.

However, a perfectly viscosity free system might not be allowed in nature. There is a conjecture, based on string theory calculations that there is a lower bound such that η/s must be greater than $1/4\pi$ [4]. The anisotropies measured in heavy ion collisions limit η/s to a few times $1/4\pi$ currently, but a precise value as a function of temperature is not yet known [5]. What is interesting is that even the limits which already exist make the QGP one of the most perfect fluids in nature. The η/s of the QGP is at least 5 times smaller than that of water.

We don't have a way to directly measure η/s of the QGP. Instead, computer simulations of fluid motion, hydrodynamics, can be run with different values of η/s and compared to data. Of course, there are other parameters in these calculations so the key to precisely determining η/s is to constrain everything else about the hydrodynamic calculations as accurately as possible.

Experimentally, we're interested in how well the geometry of the initial state is propagated to the final state correlations. If the shape of the collision is the same, will the v_2 remain constant or does it depend on some other property of the collision. Two properties that the v_2 might depend on are the size of the collision region or the energy of the collision.

In order to quantify this, there needs to be a measure of the shape of the collision region. For smaller impact parameters (a small separation between the centers of the nuclei), the shape of the initial state is more circular and as the impact parameter becomes larger the initial state becomes more elongated. We can characterize this via an eccentricity:

$$\varepsilon_2 = \frac{\sqrt{\langle r^2 \cos 2\phi \rangle^2 + \langle r^2 \sin 2\phi \rangle^2}}{\langle r^2 \rangle} \tag{2}$$

The ε_2 of a circle is zero and the ε_2 of a line segment is one.

As the eccentricity decreases, the magnitude of the angular modulation is also observed to decrease. We can exploit the difference in collision energy between RHIC and the LHC to isolate the effect of the geometry of the collision from the collision energy. Because of the higher collision energy at the LHC for a fixed eccentricity more particles are produced at the LHC than at RHIC. It is therefore possible to determine if the shape of the collision alone determines the observed v_2. To do this, v_2/ε_2 is measured as a function of the number of particles produced in the collisions,

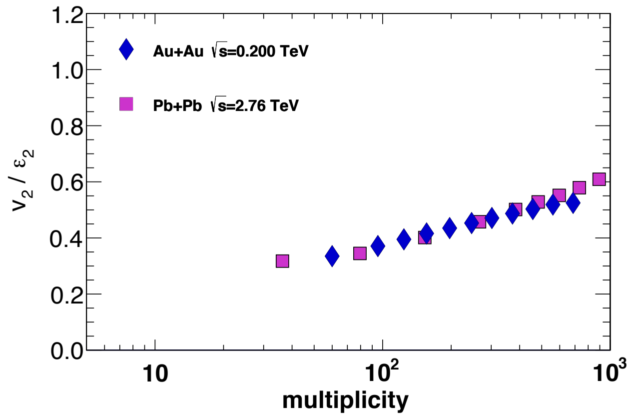

Figure 4: Ratio of the anisotropy, v_2 to ε_2 as a function of the number of particles produced in the event (multiplicity) for collisions of gold nuclei at RHIC (diamonds) and lead nuclei at the LHC (squares). Despite the factor of 15 difference in the collision energy, both sets of points have a common value at fixed multiplicity. Figure adapted from Ref. [6].

multiplicity, for gold-gold collisions at RHIC and lead-lead collisions at the LHC, as shown in Figure 4. Two features are notable. First, v_2/ε_2 is not constant as a function of multiplicity. Second, it is the multiplicity and not the collision energy which determines v_2/ε_2.

3 Small Size Limit of the QGP?

In Figure 4 the relationship between v_2 and ε_2 holds to the smallest particle multiplicities for which data exists. Where does this relationship break down? If the v_2 is caused by the presence of a QGP, is it possible to make a system small enough that v_2 vanishes and the QGP would not be observed?

Recently, proton-lead collisions were measured at the LHC, in order to study the nucleus in the absence of QGP effects. Shockingly, however, they found a non-zero v_2 [7, 8]. The pressing question then, is whether this observed v_2 from hydrodynamics in the quark-gluon plasma as in nucleus-nucleus collisions or does it have some other origin?

In a proton-lead collision, the small proton hits only a small area of the much larger lead nucleus resulting in a collision region that is roughly circular, but much smaller than in central heavy ion collisions, Figure 5. This breaks some of the correlation between ε_2 and multiplicity in heavy ion collisions.

A powerful test to see if the v_2 observed in highly asymmetric collisions is related to the initial geometry of the collision is to vary the shape of the overlap region, while keeping the small nucleus very small, and see if the v_2 varies with the eccentricity, as was seen for heavy ion collisions in Figure 4. To do this, we look at successively larger small nuclei. The proton is a nucleus consisting of a single nucleon. The next larger nucleus is the deuteron (d), an isotope of hydrogen composed of a proton and a neutron. The shape of this nucleus is elongated like a dumb-bell; therefore, it will have a large eccentricity. When a deuteron is collided with a much larger nucleus (in this case gold) the orientation with which the dumb-bell hits the gold nucleus will vary from collision to collision, however on average ε_2 for deuteron-gold collisions must be larger than for proton-lead collisions. An illustration of a single deuteron-gold collision is shown in Figure 6.

Because of the much smaller number of particles produced in a deuteron-nucleus collision compared to a collision of two large nuclei, it is much harder to reconstruct the orientation of the overlap region within an event. A different experimental technique is warranted here.

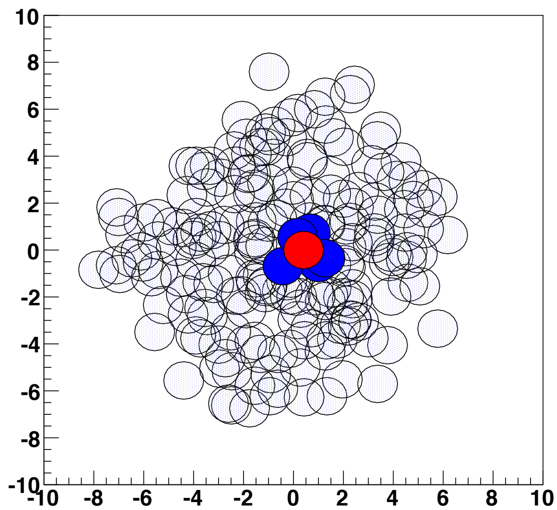

Figure 5: Simulation of the nucleon positions for a single proton-gold collision. The proton itself is shown in red and the nucleons which are hit from the gold nucleus are shown in blue.

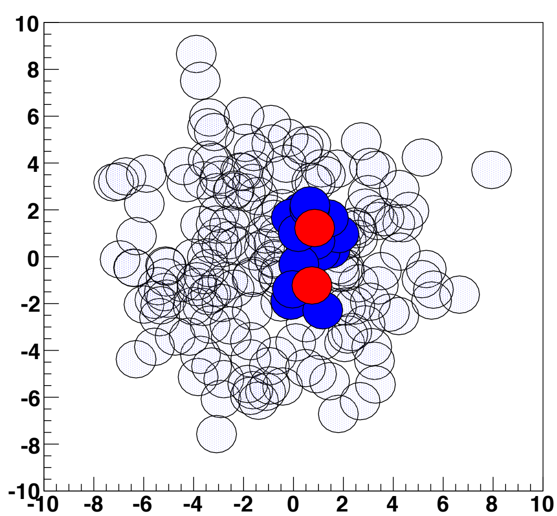

Figure 6: Simulation of the nucleon positions for a single deuteron-gold collision. The two nucleons from the deuteron are shown in red and the nucleons which are hit from the gold nucleus are shown in blue.

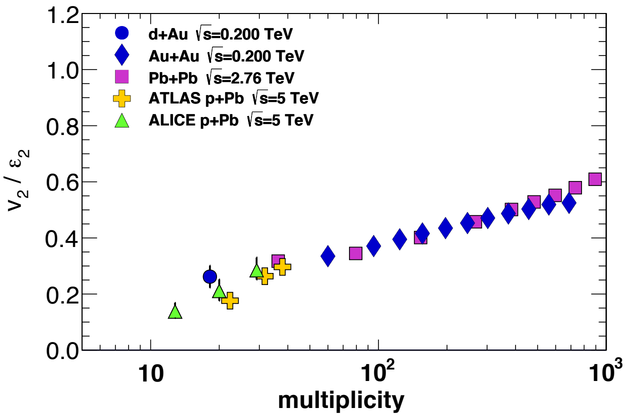

Figure 7: The same data has in Fig. 4. Now proton-lead collisions from the LHC (crosses and triangles) and deuteron-gold collisions from RHIC (circles) are added to the plot. Figure adapted from Ref. [6].

The particles individually are all influenced by the orientation of the overlap region. Any one particle however has poor resolution for identifying that orientation. We look then at the correlations of all particle pairs in the event. Since each particle was influenced by the same collision geometry there is a small preference for getting pairs either nearby in the angle perpendicular to the beam direction of back-to-back in that same angle (π radians apart). There are many other processes that can cause such signals, but when an estimate of those is subtracted we are left with a curve in which the modulation is proportional to v_2^2.

The v_2/ε_2 for heavy ion, deuteron-gold and proton-lead collisions is shown in Figure 7. This common scaling from very large to very small collisions suggests that similar matter is being made in all the systems. However, the ratio v_2/ε_2 is not constant as a function of the number of produced particles; the ration between v_2 and ε_2 is not independent of the size of the system. This could be telling us a few things. First the eccentricity is calculated by making some assumptions about how the positions of the nucleons translate into the geometry of the initial state of the hydrodynamic calculation. As the system becomes smaller those details matter more. Secondly, the smaller system lives a shorter time and is more sensitive to the effects of viscosity. Understanding the relative interplay of these two effects is key to quantitatively understanding the viscosity of the quark-gluon plasma.

Exploring more small nuclei is key to further validating this paradigm and exploiting it to constrain the viscosity of the QGP. To that end, ^{3}He-gold collisions were recently measured at RHIC. ^{3}He is the next largest nucleus after the deuteron. Whereas the deuteron can impose an elongated shape on the larger nucleus, with a large ε_2, ^{3}He can impose a triangular shape on the larger nucleus. The shape is characterized by the triangularity, ε_3 and the resulting correlations are not v_2, but v_3, with a $\cos 3\phi$ angular modulation. Analyses of these data are underway.

4 Conclusion

The similarities between observations in small and large collision systems at both the LHC and RHIC have provided many surprises. Recent data on ^{3}He-gold collisions will be key to validating this paradigm. Small collision systems have the potential to provide unique constraints on the initial geometry of the collision systems as well as the viscosity of the QGP.

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